Impact of Track Structure Effects on Shielding and Dosimetry

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INTRODUCTION.

Galactic cosmic rays (GCR) consisting of nuclei of all the known elements with kinetic energies extending from tens to millions of MeV pose a significant health hazard to future deep space operations. Even half of the radiation exposures expected in ISS will result from GCR components. The biological actions of these radiations are known to depend on the details of the energy deposition (not just linear energy transfer, LET, but the lateral dispersion of energy deposition about the particle track). Energy deposits in tissues are dominated by the transfer of tens to hundreds of eV to the tissue's atomic electrons. In the case of low LET radiations, the collisions are separated by large dimensions compared to the size of important biomolecular structures. If such events are also separated in time, then the radiation adds little to the background of radicals occuring from ordinary metabolic processes and causes little or no biological injury. Hence, dose rate is a strong determinant of the action of low LET exposures. The GCR exposures are dominated by ions of high charge and energy (HZE) characterized by many collisions with atomic electrons over biomolecular dimensions, resulting in high radical-density events associated with a few isolated ion paths through the cell and minimal dose rate dependence at ordinary exposure levels. The HZE energy deposit declines quickly laterally and merges with the background radical density in the track periphery for which the exact lateral distribution of the energy deposit is the determinant of the biological injury. Although little data exists on human exposures from HZE radiations, limited studies in mice and mammalian cell cultures allow evaluation of the effects of track structure on shield attenuation properties and evaluation of implications for dosimetry.

The most complete mammalian cell HZE exposure data sets have been modeled including the C3H10T1/2 survival and transformation data of Yang et al.[1], the V79 survival and mutation data of various groups[2], and the Harderian gland tumor data of Alpen et al.[3] Model results for the Harderian gland tumor data are shown in figure 1 in comparison with data from Alpen et al.[3] The Harderian target cell initiation cross section is shown in figure 2 and compares closely with the transformation cross section found for the C3H10T1/2 cell transformation data of Yang et al. The most notable feature of the cross sections in figure 2 are the multivalued cross sections for a given LET which implies the corresponding relative biological effectiveness (RBE) is dependent not only on the LET but also the ion type. This fact is at variance with the latest ICRP recommended quality factor[4] which is a defined function of only the LET.

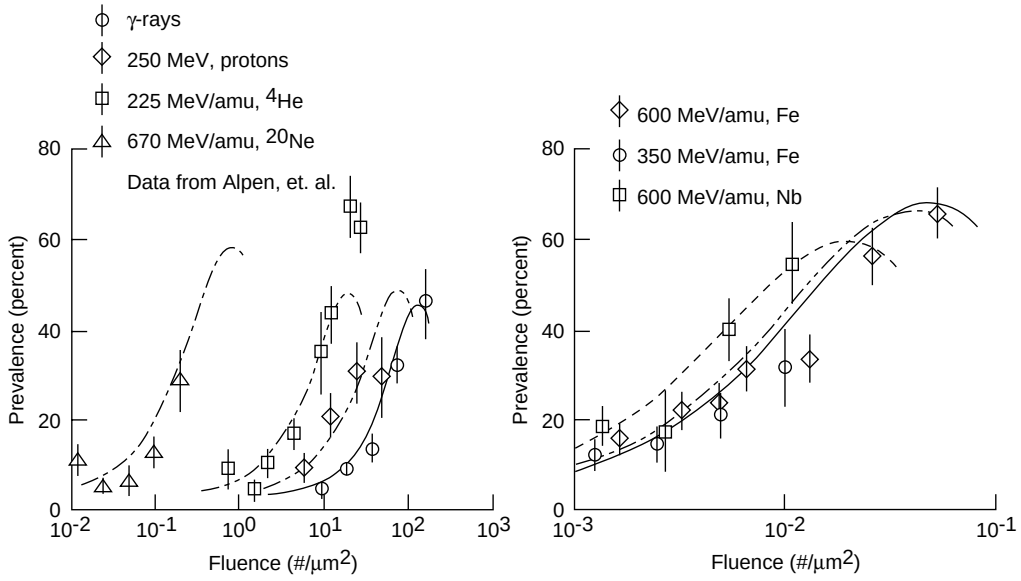


Fig. 1. Fluence response for Harderian gland tumors for several radiation types.

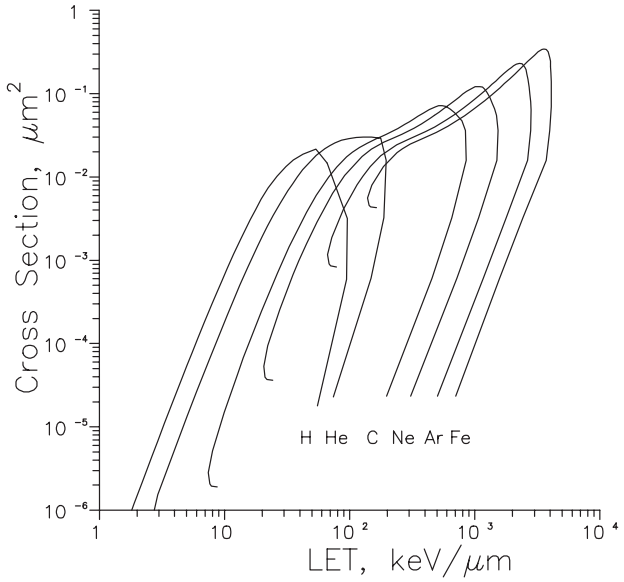


Fig. 2. Harderian gland cell initiation cross section obtained from fits to the Alpen *et al*. data.

Track structure related events are difficult to study in whole animals since the local environment within an animal varies across the organ under study and is modified by the surrounding tissues. Cell cultures can be used to control the local environment and provide an improved system for track structure studies. Among the best studied cell systems is V79 for survival and mutation end points. The model of the V79 system is shown in comparison with data from various groups in figure 3[2]. As we shall see, these features have important implications for attenuation of biological effects within spacecraft materials.

IMPACT ON SHIELDING.

We have used these models and the LET dependent quality factor[4] to investigate the attenuation of biologically damaging radiation within shield materials in the space environment[5] using the HZETRN code. In terms of dose equivalent, we find that aluminum structures attenuate radiation effects over most of the range of depths used in human rated vehicles (2-10 g/cm^2) as shown in figure 4. In contrast, track structure models show markedly different attenuation characteristics and, in fact, show that a transformed cell is more likely to result by increasing the aluminum shielding in spite of the decreasing dose equivalent. Such findings may have important implications for deep space exploration[6] but also for ISS which receives half its exposure from GCR ions.

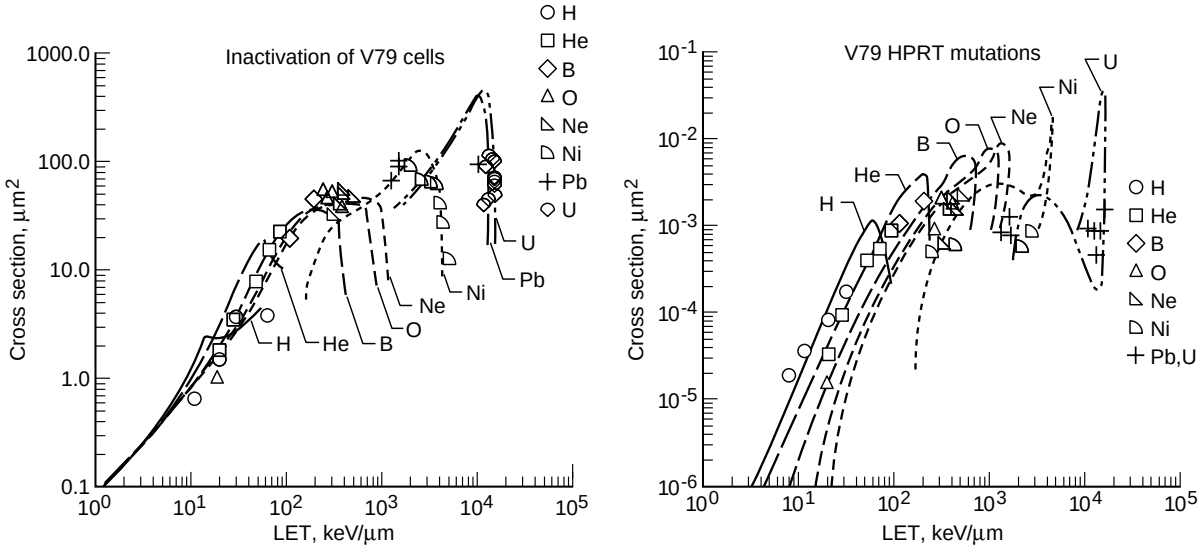
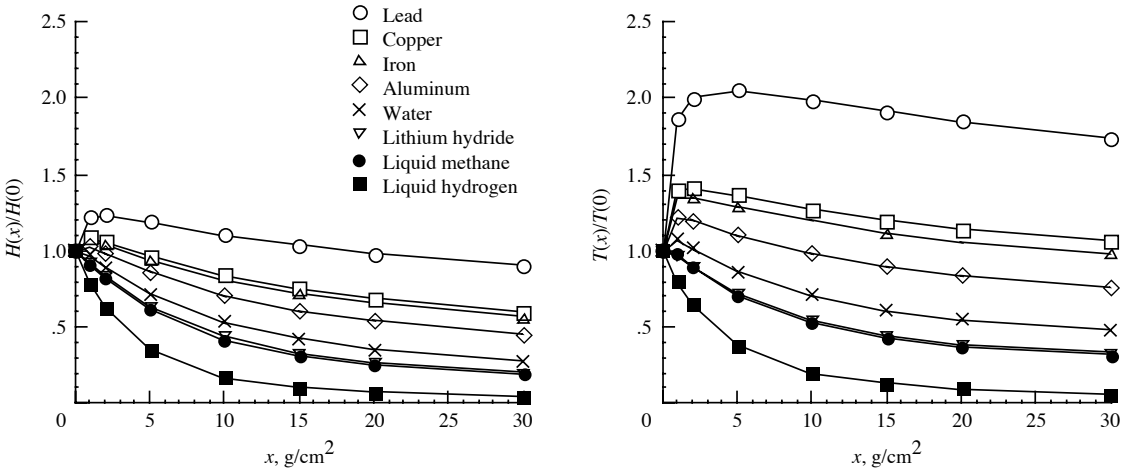


Fig. 3. Track structure effects in the V79 cross sections for (a) inactivation and (b) HPRT mutation.



(a) Dose equivalent **(b) Cell transformation**

Fig. 4. Attenuation of dose equivalent and cell transformation for a one-year GCR exposure at solar minimum behind various shield materials.

DISCUSSION.

The biologically based models show complex dependence on radiation quality which is expressed in terms related to the details of the particle track as distinct from the simple LET dependence of the quality factor used in conventional radiation practice. Even the cancer risk attenuation characteristics of spacecraft shield materials are found to be vastly different for the track structure dependent and LET dependent models[5] leading one to conclude that any useful dosimetric technique must reflect these differences as well. Most important in this respect is that LET dependent quality factors overestimate the effectiveness of most shielding materials and would falsely indicate reduced cancer risk. Clearly, the dosimetric quantities used to monitor risk must be carefully chosen to ensure adequate representation of track structure effects.

Sufficient knowledge of the radiation components at specific tissue sites must be the aim of the dosimetric system. Aside from LET as an indicator of radiation quality, the lateral spread of the track (which is related to ion speed and the fluctuations along the track length related to the effective charge) needs to be adequately taken into account. Although microdosimetry could possibly provide some details, the current site sizes are limited by current technological capability and are probably too large to adequately represent the details available in some current biological data (fig. 3). The representation of such details is presently available in a fluence based model (used herein) requiring the specification of the particle spectral environment and is the only method known that can adequately represent biological risks.

CONCLUSIONS.

Just as the estimation of shield attenuation characteristics of various materials depends on the details of the biological response model, the impact of the requirements for dosimetric characterization of the radiation fields depends on the biological model used in risk assessment. In that the experimental biological evidence displays clear dependence on other parameters in addition to LET, the adequate estimation of risk in future deep space missions needs to reflect this dependence on these other factors. One test of an adequate dosimetry system would be to assure that the track structure dependent data already derived from heavy ion experiments can in fact be represented (e.g., the data in figure 3). Failure to do so could be an indication of the inadequacy of the dosimetric system. The only method known to date to pass such a test is a fluence based risk assessment method as used in the present paper.

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